Early Time Optical Emission from Gamma-Ray Bursts

Drejc Kopač, Andreja Gomboc, and Jure Japelj
Faculty of Mathematics and Physics, University of Ljubljana, Slovenia

1 Introduction

Early time optical emission (i.e., emission before $\sim 10^3$ sec after the GRB trigger) is an important tool to study the physics of Gamma-Ray Bursts (GRBs). Especially when it is detected during the ongoing gamma-ray emission, early time optical emission can help us understand true mechanisms behind prompt GRB emission and provide constraints on current and future GRB emission models.

In the last decade, the number of GRBs with early time optical detection has become large enough to allow various statistical studies (e.g., [1], [2]). This was made possible due to fast and accurate GRB localizations by the *Swift* satellite, immediate dissemination of GRB position via the Gamma-ray Coordinates Network, and due to growing number of rapid-response, fully autonomous optical telescopes. Furthermore, robotic telescopes or large field of view surveys are capable of detecting optical emission from GRBs during the still ongoing prompt gamma-ray emission, and are thus providing a growing sample of GRBs with contemporaneous gamma-ray and optical detection.

By selecting a heterogeneous subsample of 18 GRBs showing *optical peaks* during the ongoing gamma-ray emission, we performed an extensive temporal and spectral analysis of prompt optical emission. Here we discuss these results in a broader context of early time optical emission classification, and explore how early time optical polarimetry could serve as an important tool to study the mechanisms of prompt optical emission.

2 GRBs and early time optical emission

In the most commonly accepted theoretical interpretation, the fireball model is invoked to explain GRB emission. Central engine (presumably a black hole – accretion disk system) pumps out a pair of opposite jets, which are powered by the accretion of matter. Ultra-relativistic shells with different bulk Lorentz factors are ejected, leading to relativistic shocks which take place inside the outflow (internal shocks) and give rise to the prompt gamma-ray emission. When relativistic shells hit the external medium (external shocks), they are decelerated and the result is emission at longer wavelengths, called the afterglow. Currently, mainly because of the rich variety of available experimental data, the external shock region is understood better than the internal shock region, where a consensus about the dominant dissipation mechanism has not yet been reached [3]. Various processes likely play an important role in providing the dissipation and emission, e.g., relativistic shocks, magnetic reconnections, inverse Compton scattering, etc. Central engine region is understood poorly, since we only have indirect evidence about the nature of progenitors.

Prompt optical emission offers a direct probe to better understand the internal shock region, and thus the acceleration and dissipation processes which power GRBs. By analyzing the temporal profiles of prompt optical light curves, we can compare the characteristic time scales and temporal structure with those of prompt gamma-ray light curves. Multi-wavelength spectral analysis can show if the spectral energy distribution is consistent with synchrotron emission, and whether optical and gamma-ray emission originate from the same emission processes.

3 Analysis of prompt optical peaks

The motivation for our study was GRB 090727, which was detected by the *Swift* satellite and observed promptly by the Liverpool Telescope (see [1] and references therein). This GRB showed a steep optical peak, which happened when the high-energy (gamma-ray and X-ray) emission was still active (see Figure 1, panel "090727"). Our modeling showed that the most likely scenario is that optical and high-energy peaks are not completely simultaneous, and more importantly, that the optical peak is not consistent with the interpretation in the context of the standard reverse external shock emission, because it is too steep. To put this result in a broader context, we selected a heterogeneous sample of 18 GRBs which show early time optical peaks occurring during the still ongoing gamma-ray emission (Figure 1).

By performing a detailed temporal analysis of optical peaks in our sample, we obtained rise and decay indices, peak times (t) and the peak durations (Δt). We found that in many, but not all cases, prompt optical peaks are very sharp, meaning that their durations are smaller than their peak times ($\Delta t/t < 1$), which implies an internal shock origin. Also, their rise ($\alpha_{\rm rise}$) and decay ($\alpha_{\rm decay}$) power-law indices are in many cases very steep and therefore inconsistent with the predictions of the standard afterglow emission theory. Figure 2 (left panel) shows power-law indices of these peaks, and the size of the circle around each point represents the relative value of $\Delta t/t$; smaller circle means lower $\Delta t/t$ and thus sharper peak. It is evident that steeper and sharper peaks likely do not correspond to afterglow emission (and do not populate the grey area in Figure 2, left panel).

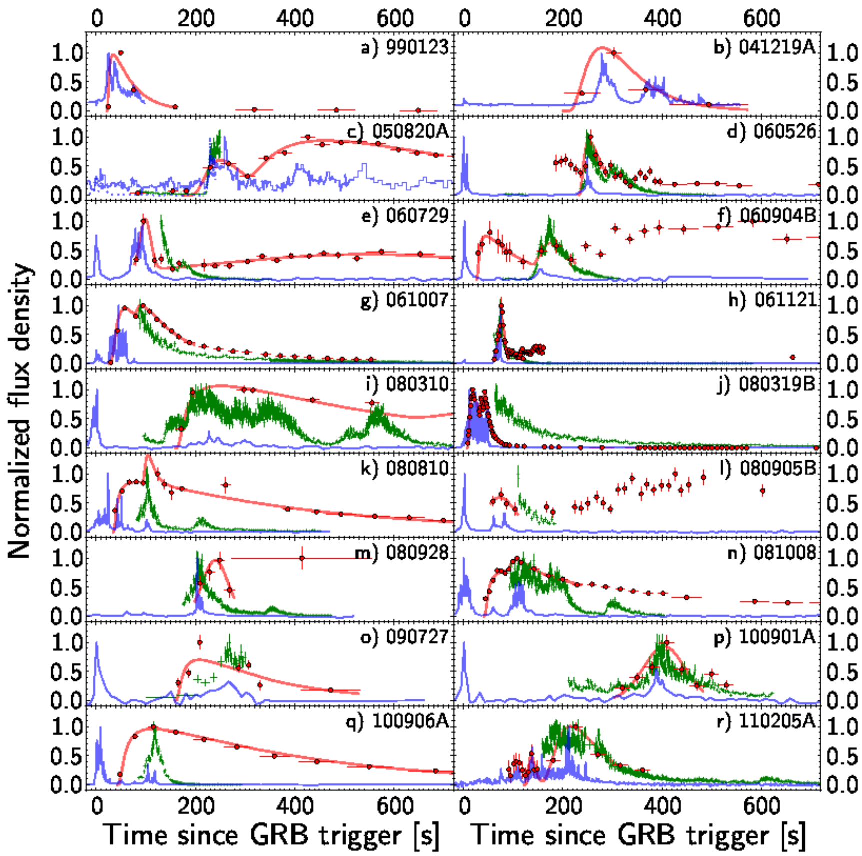

Figure 1: Optical (red), gamma-ray (blue) and X-ray (green) normalized light curves of GRBs showing prompt optical peaks [1].

Our spectral analysis showed that gamma-ray and optical-to-gamma-ray extrapolated spectral indices, obtained by fitting the spectrum with simple power-law behaviour ($F_\nu \propto \nu^{-\beta}$), are consistent with the synchrotron emission from relativistic electrons. Furthermore, the ratio of fluxes between gamma-ray and optical emission, $(\nu F_\nu)^\gamma/(\nu F_\nu)^{\rm OPT}$, showed that the diversity is large, as the distribution of flux ratios spans over 5 orders of magnitude (Figure 2, right panel, green and blue histograms).

Such diversity in measured parameters, both temporal and spectral, implies some random processes and points towards prompt phase origin. We thus performed a simple internal shock dissipation simulation, where two ultra-relativistic shells collide and produce a pair of internal shocks, one forward and one reverse, similarly as in the external shock scenario. By simulating a number of such collisions within the parameter space of typical GRB properties, we predicted the observed flux in gamma-ray and optical regime using synchrotron emission theory (see [1] and references therein). The simulated distribution was consistent with $(\nu F_\nu)^\gamma/(\nu F_\nu)^{\rm OPT}$

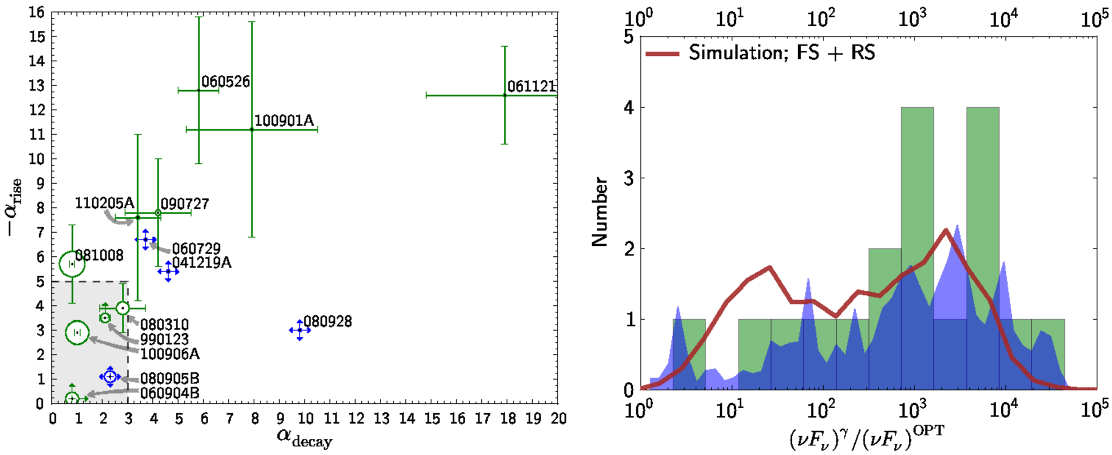

Figure 2: **Left**: $|\alpha_{\rm rise}|$ versus $\alpha_{\rm decay}$ diagram. Gray shaded area shows the region of power-law indices as predicted by the standard afterglow emission theory [4, 5]. The radius of the circle around each point represents the relative value of $\Delta t/t$. **Right**: Flux ratio distributions as obtained from observations (green and blue histograms, where blue histogram takes into account also the scatter of observed flux ratios) and from the internal shock dissipation model simulation (normalized brown solid line) [1].

distribution obtained from observations (Figure 2, right panel, brown solid line). We concluded that early time optical emission with sharp and steep peaks, occurring during the ongoing gamma-ray emission, could not be interpreted in the context of the standard external shock afterglow model, and could instead originate from dissipation within internal shock region, similarly as prompt gamma-ray emission [1].

4 Early time optical emission classification

Although sharp and steep prompt optical peaks, large diversity in temporal and spectral parameters, and consistency with internal shock dissipation simulation imply internal shock origin for early time optical emission, this is not the case for all optical peaks. Especially for GRBs where optical peaks are noticeably less sharp and steep, we can speculate that early time optical emission can represent standard afterglow emission, likely due to reverse external shock, which can manifest itself as a bright optical flash in the early time light curve[1] [6].

Furthermore, prompt optical and gamma-ray emission do not necessary originate from the same internal shock component. We can have more collisions happening at various regions in the flow, one producing brighter gamma-ray emission and other

[1]For example, this is evident for GRB 990123, where reverse external shock model can explain the early time optical light curve behavior (see [7]), and for which $\Delta t/t$ value is higher than 1.

producing brighter optical emission. In some cases optical and gamma-ray peaks could originate from just a slightly different region in the flow (different lab times and/or different radii of the expanding flow), while in others the difference between lab times is much higher, and so the temporal correlation is not a requirement. This means that in the majority of cases it is not straightforward to claim whether gamma-ray and optical peaks originate from the same region or not. Optical peak which seems "isolated" during the still ongoing gamma-ray emission could originate from internal shocks, but could as well be due to reverse external shock, other internal dissipation mechanism like magnetic reconnections, variable microphysics parameters, structured jets, etc.

To obtain more information and to better understand the early time optical emission, optical polarimetry serves as an important tool which can give more constraints on models and help determine the origin of early time optical emission.

5 Early time optical polarimetry

If GRB jets are baryonic and contain large scale and ordered magnetic fields, which could be advected from the central engine and survive long after the initial explosion, then any synchrotron emission from such medium should be highly (up to $\sim 70\%$) linearly polarized. Polarization at early times after the GRB explosion has been first measured for prompt gamma-ray emission, and especially recent results from GAP instrument proved that the degree of prompt gamma-ray polarization is indeed very high [8].

In optical regime, until 2006 polarization measurements have been performed typically around one day after the GRB trigger. In 2006, RINGO polarimeter, mounted on the Liverpool Telescope, provided the first early time optical afterglow polarization measurements for GRB 060418, and later for GRB 090102 [9, 10]. At early times, optical emission can be dominated by the reverse external shock afterglow contribution, and if the jet is magnetized, we expect to detect high degree of polarization from the reverse shock photons. In this case polarization is expected to decay with time as the reverse shock component fades and forward shock component starts to dominate the early time optical light curve. Decaying degree of polarization has been observed very recently with RINGO2 polarimeter in the case of GRB 120308A, where polarization degree of $P = 28 \pm 4\,\%$ has been measured at 4 minutes after the GRB trigger, and decreased over the next 10 minutes to $P = 16^{+5}_{-4}\,\%$ while polarization position angle remained stable [11].

The next step would be to measure polarization of prompt optical emission. RINGO3 polarimeter, currently mounted on the Liverpool Telescope, is capable of measuring polarization of the optical source brighter than 17th magnitude promptly after the GRB trigger. In case of sharp and steep optical peaks, which would occur during prompt gamma-ray emission, polarization measurements would allow to test if the degree of polarization in optical regime is very high in comparison with the polarization degree of gamma-ray emission, and whether it decays when optical afterglow emission becomes dominant. Furthermore, since prompt emission originates from regions closest to the central engine, this would help us to study the spatial evolution of the GRB outflow.

6 Conclusion

GRBs with contemporaneous optical and gamma-ray detections are an important tool to study the GRB emission mechanisms. We show that prompt optical peaks with sharp and steep morphology could originate from internal shock region. However, early time optical light curves are in many cases complex and can show contributions from various emission components. This is often connected with experimental limitations, mostly due to faintness of early time optical emission, inadequate temporal resolution of optical observations, and too long response time of robotic optical telescopes.

Early time optical polarization measurements and its temporal evolution across various phases of optical light curve, coupled with polarization measurements in other wavelengths (gamma rays and radio), will provide vital information about the nature of GRB emission.

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